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Aspects concerning the optimal development of robotic systems architecture for waste sorting tasks

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Abstract. In the last decade waste has become a real problem and therefore measures are needed to stimulate the transition from *waste as a problem* towards *waste as a resource*. Robotics technology together with advanced recognition sensor are key enabler technologies that will play an important role in this transition and it is expected to significantly increase the sorting efficiency of some waste streams and replace/complement the labour-intensive manual sorting. In this context, this paper presents aspects concerning the optimal selection of robotic systems architecture for sorting solid recyclable waste streams transported with conveyor belts. An optimization algorithm based on different performance criteria to choose the best robotic system architecture is detailed in the paper too. The numerical results can be a good starting point for other researchers in the field of smart waste management solutions.

1. Introduction

Urbanization and linear economy are the major issues when it comes to waste [1-3]. Resources are being extracted and exploited to transform them into consumption goods and after End-of-Life (EoL) they become waste. In this context, measures are needed to stimulate the transition from 'waste as a problem' towards 'waste as a resource'. Circular economy can be the answer in this case, where waste is continuously recycled and becomes exactly the resource we need to produce new goods [3-6].

Almost 75% of waste can be recycled and reused, but this implies the use of an integrated waste management system where the waste is segregated at the source (dry and wet), collected, transported, transferred, sorted and recycled, composted, treated mechanically and biologically and finally stored in a unique waste disposal system. As highlighted in [7,8], the lack of modern waste sorting plants represents in many cases the biggest issue for increasing the sorting/recycling rates.

It is well known that traditional waste sorting plants are large facilities that consume a lot of energy and are based on labour-intensive manual sorting. Sorting staff can separate from conveyor belts different types of recyclable waste such as paper, blended bottles of different colours, white or coloured polyethylene sheets, etc. However, manual sorting is very expensive, has a 70% efficiency and expose human staff to various environmental hazards. Almost every time it is supported by several pre-processing and post-processing technologies to increase the productivity [7,9].

In this context, higher sorting/recycling rates can be obtained only by using some sort of automatization and emerging technologies such as Robotics, AI, Internet of Things (IoT), Big Data to name a few. Robotics technology together with advanced recognition sensor technologies can be a viable solution to replace/complement manual sorting to improve the efficiency of sorting/recycling rates. Such technologies could be particularly valuable also in waste streams containing hazardous materials, as it could enable sorting without human intervention [10]. However, it's worth mentioning that the configuration of a sorting line is highly dependable of the quality of the input waste stream and in some situation manual sorting can be a better solution or in other situation a combination of both, but if a robotic sorting system is the right solution some requirements must be fulfilled.

To conclude, the purpose of this study is to present some guidelines concerning the optimal selection of a robot architecture to be used for sorting solid recyclable waste streams transported with conveyor belts.

The rest of the paper is structured as follows: in Chapter 2 is presented the state of the art of robotics technology for waste sorting tasks, while in Chapter 3 are detailed the main guidelines concerning the optimal choice of the robotic system architecture. The analysis results are presented and discussed in Chapter 4. Finally, the paper ends up with the conclusion.

2. State of the art in robotics technology for waste sorting tasks

This chapter presents an overview of the commercial waste sorting robots that are using advanced waste identification/recognition technology to improve sorting/recycling rates.

Typically, such systems include a conveyor belt that feeds the stream waste under a sensor cabinet including NIR-near infrared sensors, 3D sensor system, Hi-res RGB camera, imaging metal detector and VIS-visual light spectrum sensor, while one or more robotic arms manipulate above the belt, sorting predefined materials as the waste stream passes underneath. The block diagram of such a system is presented in figure 1.

Such a robotized sorting system requires some sort of pre-processing operations of the waste too. As highlighted in figure 1 using chained blocks, first the waste is feed for screening to remove smaller particles and undesirable light fraction. Next, the separated waste is stored into a buffer bunker and from there in continuously feed with a vibrating screen on the conveyor belt of the robotic sorting system. Finally, the waste is sorted in predefined bunkers as it passes through robotic cell/cells. The unsorted waste bunker can be reintroduced in the circuit if sorting performance is not satisfactory.

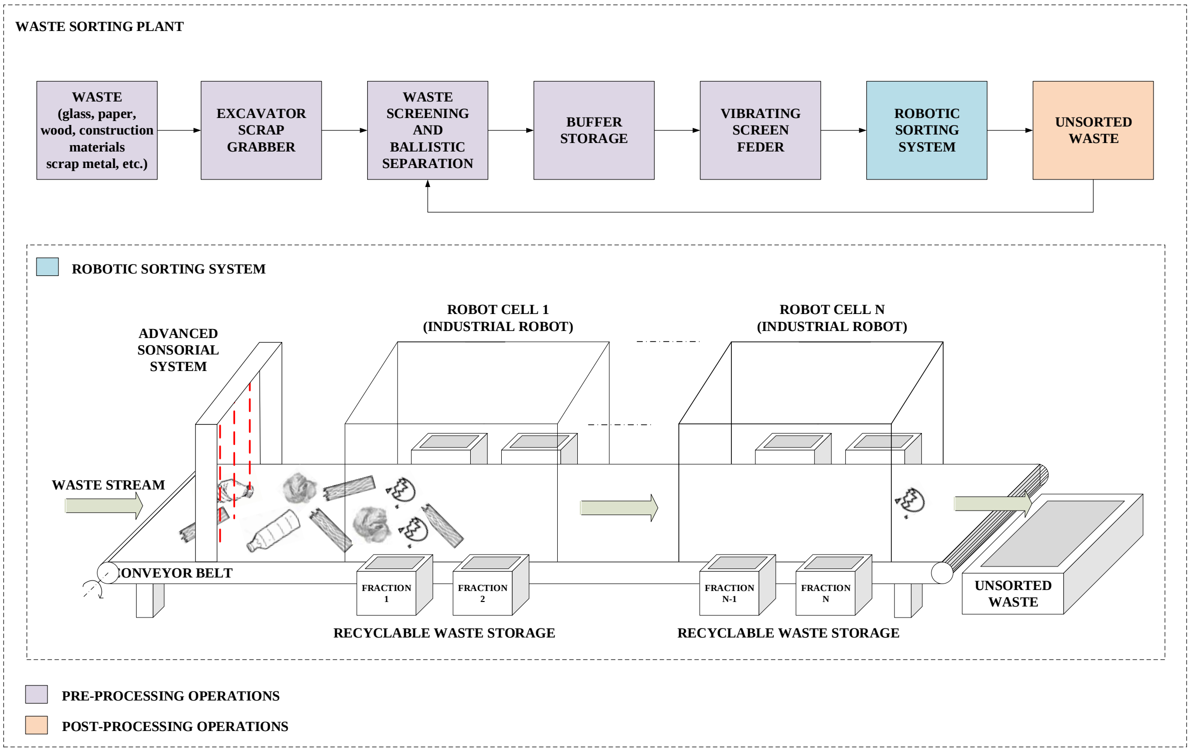

Figure 1. Block diagram of a robotized solid waste sorting plant.

For example, AMP Robotics [18] (Autonomous Manipulation and Perception) offers hardware and software solutions for waste sorting. The prototype developed by the company consist of a 3 DOF Delta parallel robot named CORTEX, which can sort recyclable materials like mixed waste, construction/demolition waste and electronic waste from a conveyor belt. It is controlled by Neuron, the artificial intelligence system that allows the identification of different types of recyclable waste from the waste stream using image processing and machine learning techniques.

On the other hand, ZenRobotics [19], a finish company, has developed two types of robotic systems: a heavy picker cartesian robot who can pick up to four different types of waste using a finger type gripper and a fast picker cartesian robot which is ideal for lightweight material such as packaging and dry mixed recyclables. The company provides also a powerful software (Waste Analysis Tool) which gives information and metrics about waste stream and recommendation concerning the optimization of sorting process.

More recently, Waste Robotics [20] has designed WR-1, a cartesian robot capable of sorting from a conveyor belt organic waste stored in green bags. The green bags are easily recognized using computer vision algorithms and picked up to be transported for biologically treatment. The robot can process between 5 and 10 tons of waste per hour.

Finally, the solution proposed by Sadako Technologies [21], Max-Al Autonomous QC, is a Delta parallel robot system capable of sorting solid waste from a conveyor belt. The robot can identify different types of waste rapidly by processing video images with the help of the sensorial system and neural networks. Neural networks are ‘machine learning’ models based on human brain architecture. The robot takes decisions through experiences previously taken from other recycling operations.

Two important conclusions can be drawn from this analysis. First, the configuration of a sorting line is highly dependable of the input waste stream. After all, the purpose of such system is to replace/complement manual sorting and the quality of the waste stream dictates the sorting performance of the system.

Second, an important decision to be made when designing such a system is how to optimally choose the best robotic systems architecture. Although commercial robotic systems for sorting waste exists, there are no guidelines regarding the proper selection of robot architecture for waste sorting tasks. In this context, next chapter will present an optimization algorithm based on different performance criteria to choose the best architecture.

3. System architecture multi-criteria analysis

Like many other systems, designing of robotic systems take into account the range of tasks that a robot has to perform [11]. The robot must be designed in such a way that it can execute the task for which it is intended. So, the destination and task influence the architecture of robot, the number of joints, physical size, payload capacity, end-effector movement and also performance indices.

3.1. System destination and task definition

Based on previous explanations, given the specificity of the task, we can define the robotic system's destination and task as follows:

Working environment: dust-loaded environments, specially sites for waste processing and selection
Needed workspace: parallelepiped (L x W x H = 2 x 2 x 0.5m^3)
Load type: dry solid waste (wood, brick, metal)
Handled mass (load): 0-3 kg
State of manipulated objects: in movement (low variable velocity)
End-effector mobility: T(X,Y,Z), R(Z); 4-DOF;
Gripper: special construction (2kg)
End-effector velocity, acceleration: 3m/s, 2m/s^2

The end-effector of manipulation system must be able to execute four movements: three translations (along X, Y and Z) and one rotation (around Z). The takeover of the waste objects is ensured by the proper orientation of the end-effector around Z axis, respectively by the clamping the object with a dedicated gripper to handling dry solid wastes. Waste is pre-processed so that the robotic system could take them off a conveyor belt and sort them appropriately, depending on the type of waste.

The conventional architecture of robotic systems that can perform the imposed end-effector motion is: serial, parallel or mixed, with a minimum 4-DOF mobility of the end-effector. Today, for conventional manipulation tasks, there are robotic structures that are tested and certified by industrial practice. Taking into account the design requirements previously defined, but also the entire range of industrial robots, the architectures which fulfil the imposed requirements are: gantry systems (PPPR), SCARA robots (RRRT), 5-DOF and 6-DOF articulated robots, 4-DOF parallel robots like Delta, Linapod, Tripod and also 5-DOF and 6-DOF parallel structures.

The issue is now transferred into the space of the multi-criteria optimal selection of the structure that can fulfil the imposed requirements, from the set of above. The rest of the possible theoretical configurations is excluded from the analysis because of manufacturing difficulties or due to the fact that they are not used in the industrial space. The problem of choosing the optimal robotic structure to accomplish a given task is critical. In this context, an optimal choice involves a multi-criteria analysis, and then designing a system that allows the task to be performed at the imposed performance parameters but subordinated to imposed criteria and at the lowest cost of production and operation.

3.2. Multi-criteria optimal selection

Different methods like Analytic Hierarchy Process (AHP) [12], Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) [13], Analytic Network Process (ANP) [14] could be used in order to solve the issue of an optimal decision. The Analytical Hierarchy Process (AHP) is a flexible and powerful multi-criteria decision-making tool, with utility in various domains, from economic to technical areas [15,16].

In the context of AHP method, a set of evaluation criteria is defined and, based on a set of alternative options (known and user defined), the best option (solution) should be identified. Based on decision maker specifications, the method generates a weight for each evaluation criterion. For a given criterion, AHP assigns a score to each option and then combines the criteria weights and option scores, resulting in a global score for each option. It is important to note that the best option is not necessarily the one that optimizes a certain single criterion, but rather the one that makes the most appropriate compromise between the different criteria.

3.3. Criteria definition and hierarchical organization

The evaluation criteria are defined by the decision-maker based on the assessment of the most important indices that need to take into account in the analysis and decision. For current analysis it was identified three main criteria, each of them with many sub-ordered criteria (figure 2), as it follows (table 1):

Table 1. Criteria definition.

Cod	Criteria	Assessment
C1	Technical criterion	Takes into account the robot task and performance indices
C1.1	Workspace/Size	Takes into account the robot size for a given workspace
C1.2	Payload capacity	Maximum handled mass for a given workspace
C1.3	Dynamic performances	The processing time for a predefined usual manipulation task
C1.3.1	End-effector velocity	Maximum velocity for a given load

C1.3.2	End-effector acceleration	Maximum acceleration for a given load
C1.4	Complexity	Takes into account difficulties to actuate and control the system
C1.4.1	Degree of freedom (DOF)	Numbers of robot actuators
C1.4.2	Physical size	Total mass of robot (except control components)
C2	Environment criterion	Takes into account destination and environment specifications
C2.1	Environment	Influence of the environment on the robotic system
C2.2	Protection	Protection equipment against environmental actions
C3	Economical criterion	Takes into account production and operation costs
C3.1	Production cost	Acquisition cost for similar industrial systems
C3.2	Maintenance cost	The costs of system maintenance in the operation

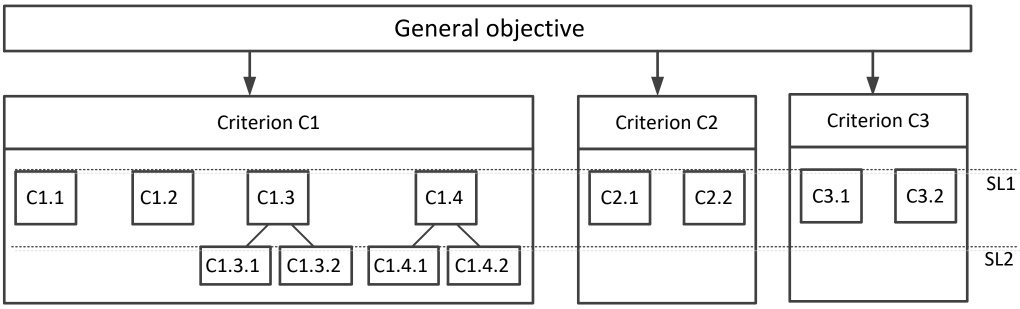

Figure 2. The hierarchical tree of criteria.

3.4. Alternative options

In table 2 are detailed the robot architectures which fulfil the imposed requirements. Some important criteria, such as accuracy, repeatability, resolution, dexterity, manipulability, were excluded through analysis because all alternative options check these indicators. So, there is no requiring the inclusion of these criteria in the analysis.

Table 2. Alternative options.

Cod	**Type***	**End-effector mobility****
A1	SR (4-DOF) – SCARA	T(X,Y,Z), R(Z)
A2	SR (4-DOF) – Cartesian	T(X,Y,Z), R(Z)
A3	SR (5-DOF)	T(X,Y,Z), R(X,Z); T(X,Y,Z), R(Y,Z)
A4	SR (6-DOF)	T(X,Y,Z), R(X,X,Z)
A5	PR (4-DOF) - Delta	T(X,Y,Z), R(Z)
A6	PR (4-DOF) - Linapod	T(X,Y,Z), R(Z)
A7	PR (4-DOF) - Tripod	T(X,Y,Z), R(Z)
A8	PR (5-DOF)	T(X,Y,Z), R(X,Z); T(X,Y,Z), R(Y,Z)
A9	PR (6-DOF)	T(X,Y,Z), R(X,X,Z)

* SR – Serial Robot; PR – Parallel Robot; DOF – Degree of Freedom
** T(X,Y,Z) – axial translations along X,Y,Z; R(X,Y,Z) – axial rotations around X,Y,Z

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4. Analysis results

Assuming that the evaluation criteria are defined, and alternative options are known, AHP implementation involves the following steps [17]: generating the pairwise comparison matrices, computing the vector of criteria weights, computing the matrix of option scores, ranking the options, and consistency evaluation. In figures 3 and 4 are presented the analysis results.

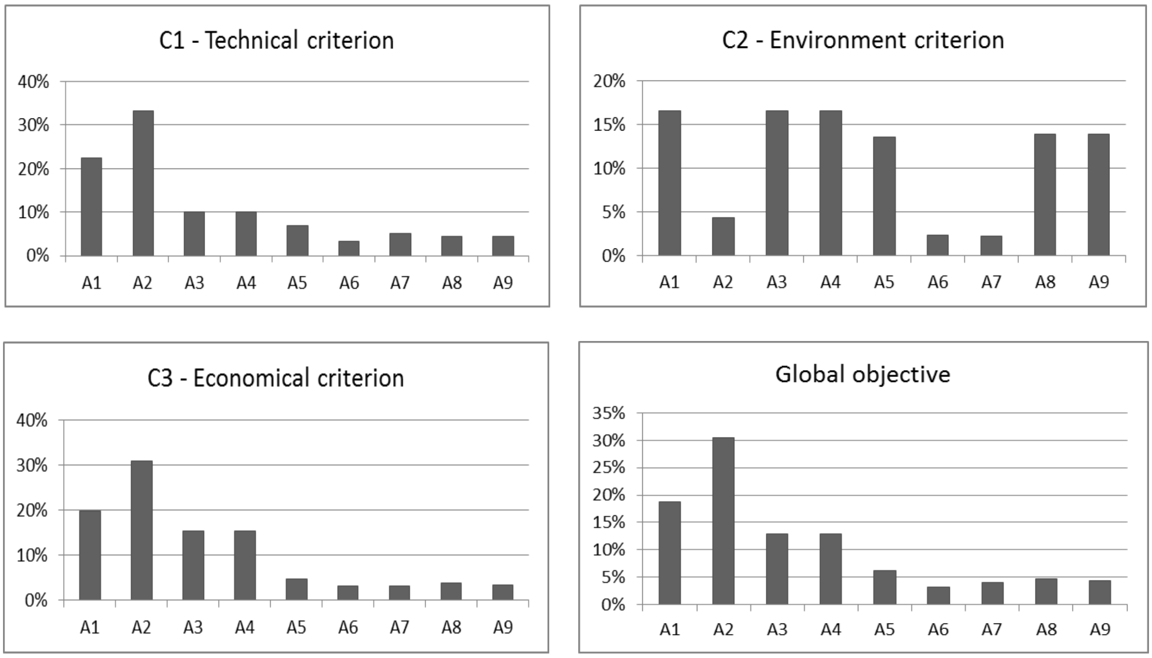
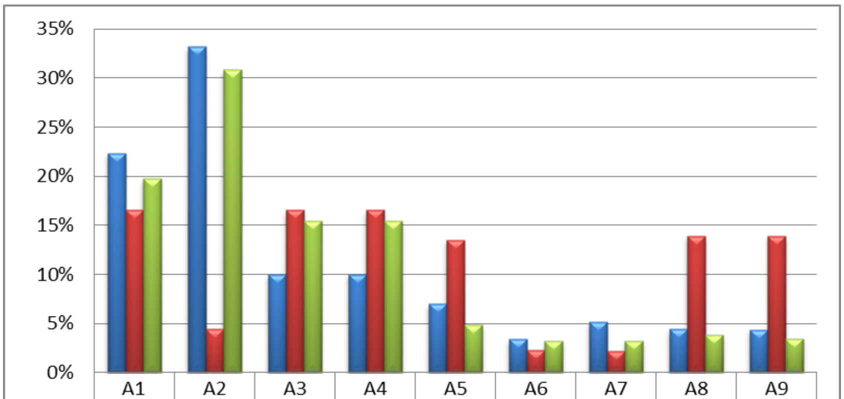


Figure 3. The distribution of local and global weights.



	A1	A2	A3	A4	A5	A6	A7	A8	A9
C1	22.34%	33.21%	10.02%	10.02%	7.00%	3.43%	5.16%	4.42%	4.40%
C2	16.56%	4.41%	16.56%	16.56%	13.55%	2.32%	2.23%	13.91%	13.91%
C3	19.78%	30.82%	15.41%	15.41%	4.83%	3.23%	3.23%	3.83%	3.46%

Figure 4. Local weights distribution. Comparative results.

Referring to the general objective, but also to technical and economic criteria, the Cartesian robots, SCARA robots and then the serial ones are clearly highlighted in the set of analyzed systems. This is due in particular to their simplicity and lower cost. The high speed of the parallel robots is not enough to recommend it for this type of task.

Referring to the environmental criterion, robots which are fitted with linear motors are more affected by environmental action due to the guides that come into permanent contact with the environment (dust-loaded) and due to the difficulty of protecting linear versus rotary motors, too.

5. Conclusions
When it comes to waste it's all about thinking *circular*. Recycling it's a major need for the present days and for the future generations. Increasing sorting/recycling rates it's an important problem which cannot be solved in the absence of modern robotized plants to speed things up. In this context, this paper presented various aspects concerning the optimal selection of robotic systems architecture for sorting solid recyclable waste streams transported with conveyor belts. An optimization algorithm based on different performance criteria to choose the best mechanical architecture has been presented to illustrate the advantages of such an approach. Finally, the analysis results presented in this paper can provide useful insight into the optimal design of robotic systems architecture for waste sorting tasks to other researchers in the field of smart waste management.

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